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Use of alternative water sources in irrigation: potential scales, costs, and environmental impacts in California

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Abstract

Under the risk of drought, unreliable water supplies, and growing water demand, there is a growing need worldwide to explore alternative water sources to meet the demand for irrigation in agriculture and other outdoor activities. This paper estimates stocks, production capacities, economic costs, energy implications, and greenhouse gas (GHG) emissions associated with recycled water, desalinated brackish and seawater, and stormwater in California, the largest US state and the most significant fresh and processed food producer. The combined recycled water and stormwater supply could increase the share of alternative water use in urban land irrigation (parks and golf courses) from the current rate of 4.6% to 48% and in agriculture from 0.82% to 5.4% while increasing annual water costs by $900 million (1.8% of California's annual agricultural revenue) and energy use by 710 GWh (0.28% of California's annual electricity consumption). The annual supply of alternative water greatly exceeds the amount of water currently used in the food processing industry. In case studies of high-value agricultural produce, conventional water use was found to contribute approximately 17%, 12%, 4.1%, and 1.7% to the total GHG emissions of avocados, lemons, celery, and strawberries, respectively. However, materials (mostly packaging) contribute 46%, 26%, 47%, and 66%, and diesel use on farms 18%, 28%, and 14% for lemons, celery, and strawberries, respectively (data for avocados were not available). Switching to recycled water or stormwater would increase the total GHG emissions of one serving size of packaged strawberries, celery, lemons, and avocados by 3.0%, 7.8%, 11%, and 27%, respectively, desalinated brackish water by 23%, 58%, 150%, and 210%, and desalinated seawater by 35%, 88%, 230%, and 320%. Though switching to alternative water will increase costs, energy demand, and GHG emissions, they could be offset by turning to less environmentally damaging materials in agricultural production and sales (especially packaging).

Background

The use of alternative water sources (other than surface or groundwater), such as recycled water, brackish water, seawater, and stormwater, has been practiced in many regions of the world and for many types of irrigation such as agricultural crops, golf courses, forests, and open-space landscapes [1–6]. Under the changing precipitation patters due to climate change, pressure of growing populations, and risk of drought, a well-articulated need is forming in parts of the world to explore additional and more reliable water sources to meet the future demand of water in agriculture and other outdoor irrigation. Many cities have formed near traditional agricultural areas and are located close to salt water. These proximities provide an opportunity for the use of alternative sources of water.

Agriculture accounts for a large share of water consumption. As the largest agricultural producer in the United States by value, California is a great case study of opportunities, challenges, and past and current practices with respect to water. Farmers used 40 billion m^3 of water for agricultural irrigation in 2015 [7] (the most recent year for which statistics are available). Although total water use in California decreased from 114 billion m^3 in 2010 to 79 billion m^3 in 2015 [7] due to more efficient water use and decline in agricultural production, groundwater extraction increased from 15 billion m^3 to 28 billion m^3 in the same period. Traditionally, California's water supply has come from surface water and groundwater. The energy embodied in water supply contributes to about 19% of California's electricity consumption and 30% of its natural gas use every year [8].

The use of treated and untreated wastewater for irrigation has been documented in several countries, including Australia, Greece, Saudi Arabia, Israel, Morocco, Kuwait, and Qatar [9–11]. Under the stress of periodic drought events, Melbourne has been using recycled water from both sewage and greywater to improve its water security since the 1970s, and now is one of the most active cities using treated wastewater for irrigation [12, 13]. Not only recycled water, but also stormwater has been considered in Adelaide, with an annual capacity of capturing 20 million m^3 in 2013 to a projected 60 million m^3 in 2050 [14, 15]. The ultimate source of water is sea water. The majority of the global desalination capacity contributes to the supply of municipal water (62.3%) and industrial water (30.2%), but already 1.8% of desalinated water is used in irrigation, which is provided by 395 desalination plants [16]. For example, desalinated seawater has been used for agricultural irrigation including tomatoes and citrus trees in southeastern Spain since 2005 [17, 18].

California has been using recycled water since 1910 [19]. A recent recycled water survey indicated that 13% of California's municipal wastewater is reused [20] for various purposes such as agricultural and landscape irrigation, groundwater recharge, and geothermal energy production. Title 22 of the California Code of Regulations sets standards for the allowed uses of recycled water, including the required degree of treatment for each application. About 37% and 23% of recycled water in California are currently used in agricultural irrigation and urban irrigation, respectively [19]. Urban irrigation includes the use of recycled water for the irrigation of golf courses and landscapes. Nearly every county in California uses recycled water, but most of the recycled water treatment is concentrated in Southern California. Driven by the concern for drought and the need for a reliable and locally sourced water supply, many cities are making efforts to support their recycled water supply development [21].

Monterey County in the Salinas Valley, one of the most significant vegetable growing regions in the state, has supplied recycled water to farmers since the 1970s to mitigate the declining water level in wells and high salinity rate in the local aquifer. An 11-year pilot project of using recycled water for irrigating crops and vegetables in this region found that the crops grown with recycled water did not contain viruses, and the quality and yield of these crops was comparable to that of the control samples [22]. Nowadays, Monterey Country is the largest raw-eaten food crop area using recycled water in the United States, irrigating 4,856 hectares (12,000 acres) [23]. The benefits of recycled water include providing a constant and reliable supply, reducing fertilizer costs, and avoiding the discharge of the used water (with high nutrient loads) to water bodies.

Though the primary foci of stormwater management are flood control and water quality protection, California has begun to promote the use of stormwater for local water supply. Stormwater filtering or treatment facilities have been built in many cities, including Los Angeles and San Francisco [24, 25]. From 1986 to 2016, about 400 million m^3 of stormwater have been annually captured and used for groundwater recharging in the metropolitan area of Southern California [26]. For example, the City of Los Angeles can capture 97 million m^3 of stormwater per year and aims to increase the capture to 196 million m^3 by 2030 [27].

According to California's Water Plan Update, its 23 existing brackish groundwater desalination plants could produce 172 million m^3 of desalinated water per year, and 20 more plants are in proposal or design phases [28]. As of 2016, the 12 active seawater desalination facilities could provide a total of 77.5 million m^3 of desalinated water per year, which is less than half of the total capacity of brackish water facilities [29].

The stock of alternative water supply varies due to the inherent characteristics of the water sources. The National Resource Defense Council (NRDC) and the Pacific Institute estimated that 518 million m^3 of stormwater can be captured per year in California [19]. The Department of Water Resources estimates that the reuse of urban water could increase by 2.5 billion m^3 by 2030, which will account for about 23% of the estimated municipal wastewater [30]. The same analysis also suggests that use of stormwater could be increased by at least 1.2 billion m^3 by 2030.

Increasingly, recycled and desalinated water have been considered to supplement the demand for freshwater in California, beyond irrigation. 2%–3% of the state's urban and farm water supply is provided by recycled water, stormwater, and desalinated brackish and seawater water, and this percentage is growing rapidly [31]. Stormwater has been captured and recycled in dairy production in California. For example, Harley Farms Goat Dairy captured 151 m^3 of stormwater per year and used it for its dairy, creamery, and gardens. The water catchment and recycling system requires little maintenance [32].

Focus of study

This paper provides an overview of the alternative water supplies—and their economic and environmental costs—for irrigation of crop land, golf courses, and parks, with data as specific as available for California. Case

Table 1. Definition of the five water sources of irrigation evaluated in this study [29].

Water source	Definition
Freshwater	Surface water or groundwater with less than 3,000 mg l^{-1} of dissolved salts
Stormwater	Surface water from heavy falls of rain or snow
Brackish water	Surface water or groundwater with 3,000–30,000 mg l^{-1} of dissolved salts
Recycled water	Reclaimed water from wastewater for potable or non-potable use
Seawater	Salt water from a sea or ocean with about 35,000 mg l^{-1} of dissolved salts

studies of the potential cost and environmental increases due to the use of alternative water sources are provided for four high-value agricultural products.

Method

We have evaluated the use of four alternative water sources for irrigation: brackish water, seawater, recycled water, and stormwater. We synthesized the most recent studies on alternative water use to construct an overall view of costs, energy requirements, GHG emissions, stocks, and current production capacities of alternative water supplies in California. We selected four high-value fruits and vegetables: avocado, celery, lemon, and strawberry, to explore the energy, GHG emissions, and cost implications of using alternative sources of water. To examine the potential of using alternative water in food processing, this study also estimated the amount of water consumption in food processing in California, and the data and calculation can be found in section S8 in the Supplementary Information.

Alternative sources of water

The definitions of the five water supplies evaluated in the study are presented in table 1. Freshwater, including surface water or groundwater, has the least concentration of dissolved salts (less than 3,000 mg l^{-1}) when compared with the alternative water sources. Brackish water contains 3,000–10,000 mg l^{-1} of dissolved salts which requires removal of salinity before it can be used in irrigation. The salinity of stormwater varies with locations and seasons, and the range is 7,100 to 10,500 mg l^{-1} of dissolved salts [33]. Most recycled water does not have an excessively high level of salinity; it contains only about 200 mg l^{-1} more than potable water [2]. Our study focused on the water supply in California, but also considered national and international studies where studies specific to California were missing.

Regulatory basis for the use of alternative water for irrigation

Alternative water sources have been increasingly used for irrigation of cropland, golf courses, and open-space landscapes in California. 59% of recycled water was used in agricultural irrigation in California in 2015 [20, 34]. Regulatory standards of drinking water and alternative water sources are presented in table 2. Title 22 of the California Code of Administration sets the water recycling criteria for 43 specified uses of recycled water. Title 22 is also one of the most stringent regulations on the use of recycled water in the world [35]. Different applications of recycled water requires different level of treatments of wastewater. For example, disinfected tertiary treatment and disinfection which meets drinking water standards are required if recycled water comes in contact with the edible portion of the crop or has direct human contact. Such cases include root crops, parks and playgrounds, schoolyards, residential landscaping, and unrestricted-access golf courses [35].

In California, stormwater management practices do not require water rights permits. However, to use stormwater directly as a water supply, one may need to apply for a water right permit under the Rainwater Capture Act of 2012. The quality of stormwater reuse is often regulated under county or municipal health and safety codes by local jurisdictions in California [41]. However, there are no explicit guidelines for the use of stormwater for non-potable uses. The water quality standards for using stormwater for irrigational purpose is summarized in table 2. Note that though the other water quality parameters for recycled water are not specified in Title 22, the turbidity limit of recycled water in California is even more restrictive than the drinking water requirement. Turbidity is measured by nephelometric turbidity units (NTU), and a low NTU level means fewer particles in the water. To our knowledge, desalinated brackish water and seawater in California usually meet the drinking water standards. Four operating desalination facilities in California only provide water for potable, industrial, and institutional uses and not for irrigation [29].

Volumes of freshwater and recycled water uses for agricultural and urban land, as well as for food processing in California are summarized in table 3. Agricultural irrigation currently consumes about 40 billion m^3 of fresh water and 325 million m^3 of recycled water in California (representing 0.82% of total agricultural irrigation).

Table 2. Standards of drinking water, stormwater, and recycled water for irrigation.

Parameter	Drinking water [36, 37]	Stormwater [38, 39]	Recycled water [35, 40]
BOD	10 mg l^{-1}	10 mg l^{-1}	10 mg l^{-1}
Turbidity	5 NTU	2–3 NTU	2 NTU
TSS	30 mg l^{-1}	5–10 mg l^{-1}	30 mg l^{-1}
pH	6.5–8.5	6–9	6–9
Chloride	250 mg l^{-1}	500 mg l^{-1}	
Zinc	5 mg l^{-1}	2–160 mg l^{-1}	
Copper	1 mg l^{-1}	0.2–5 mg l^{-1}	
Pathogens		2.2–126/100 ml	

*Disinfected tertiary treatment and disinfection which meets the drinking water standards are required if recycled water come in contact with the edible portion of the crop.
**The treatment of desalinated brackish water and seawater usually meets the drinking water quality.

Table 3. Water use (in 1,000 m^3) for irrigation and food processing in California in 2018.

Water use	Irrigation: Agricultural land	Irrigation: Urban land[a]	Food processing
Freshwater [7]	39,639,018	4,238,045	230,179[b]
Recycled water [20]	325,734	202,483	n.a.
Stormwater	n.a.	n.a.	n.a.
Desalinated water[c]	n.a.	n.a.	n.a.

[a] Includes golf courses, parks, and other landscapes.
[b] Estimated by our study.
[c] Includes desalinated brackish water and seawater.

Urban land uses 4.2 billion m^3 of fresh water and 202 million m^3 of recycled water (4.8% of total urban land irrigation). Data on the use of stormwater for the listed purposes are not available, and to our knowledge, there are no data indicating that desalinated water has been applied to agricultural or urban land in California. Water use for food processing is based on our estimation, and calculations and data sources can be found in a later section.

Water cost

The summary of costs, energy requirements, GHG emissions, stocks, and current annual production volumes for freshwater, stormwater, brackish water, recycled water, and desalinated seawater (by typical water treatment facility sizes) are presented in table 4. Data on stormwater reuse for potable purposes are not available, and rainwater harvesting is not included in this study due to lack of data, but also its estimated insignificance. The cost estimates are based on information from reports between 2014 and 2016 (inflation was not considered). The cost includes facility construction, operation, water storage and treatment, and delivery.

In general, alternative water supplies are more expensive than traditional water supplies. Groundwater extraction and surface water are the two main sources of water in California, providing 84% of the state's total water supply in 2015 [7]. For potable use, freshwater is the most economically available source compared to the other four alternatives. Groundwater use costs \$0.28 per m^3 on average. Switching from freshwater to an alternative water supply would increase cost of potable use by at least 26% and as much as sevenfold. For non-potable use, the costs of providing brackish water and stormwater from large-scale facilities were less than the cost of groundwater. Desalinated seawater is the most expensive water supply among the five types of water sources.

The size of the treatment facility can significantly influence the total cost of water supply. Water cost decreases when the scale of the facility increases. For example, the cost of stormwater for non-potable use can be 3 times higher from a small-scale than from a large-scale facility. The Carlsbad desalinated seawater plant near

Table 4. Representative costs, energy requirements, GHG emissions, stocks, and current production capacities of alternative water supplies in California. The ranges of costs, energy requirements, GHG emissions, and current production capacities are presented in the columns next to the representative data.

Water source	Scale	Cost [42]		Required energy		GHG emission		Stock	Current production	
	1,000 m^3	\$ per/m^3		kWh/m^3		kg CO_2 eq./m^3		1,000 m^3	1,000 m^3/year	
Freshwater										
Surface water				0.15 [43]	0.072–0.23	0.08 [44]	0.071–0.089 [44]			
Groundwater		0.28		0.34 [43]	0.15–0.52	0.25 [44]	0.22–0.26 [44]			
Stormwater								520,000–780,000 [45]	133,000 [46]	120,000–146,000 [46]
Non-potable use	0–1,850	0.95	0.48–1.04							
	1,850–10,000	0.20	0.19–0.21	0.89 [45, 47]	0.33–1.47 [45, 47]	0.31	0.11–0.51			
Brackish water								3,900,000,000 [48]	172,160 [43]	
Potable use	0–20,000	1.31	0.83–1.49	0.94 [43]	0.47–1.4 [43]	1.6 [49]				
	>20,000	0.91	0.77–1.08							
Non-potable use		0.14 [50]								
Recycled water								1,500,000 [51]	880,362 [51]	
Potable use	0–12,000	1.87	1.59–2.17	1.05 [9]	0.86–2.28 [9]					
	>12,000	1.46	1.28–1.66			0.71 [44]				
Non-potable use	0–12,000	1.25	1.21–1.70	0.89 [47]	0.33–1.47 [47]	0.31	0.11–0.51			
Seawater								unlimited	665,820 [52]	481,000–703,000 [52]
Desalinated water	0–20,000	2.29	2.17–3.47	3.25 [43]	3.0–3.5 [43]	2.4 [49]	2.3–2.5 [49]			
	>20,000	1.72	1.69–2.06							
Carlsbad Plant	69,048	1.73 [53]								

*The cost is based on reports from 2014 and 2016. Inflation was not factored in due to low rates.

San Diego, the largest operating desalination plant in California with a capacity of about 70 million m^3 per year, can generate desalinated water at the cost of $1.73 per m^3 [53], about 6 times the cost of using groundwater. Brackish water is the second cheapest alternative water source after stormwater for irrigation, ranging from $0.77 to $1.49 per m^3. (The cost would decrease by 31% if the treatment scale of brackish water were greater than 20 million m^3 per year.) The desalination cost is strongly associated with the level of salinity removal in brackish water or seawater.

Energy requirements

Table 4 shows the average electricity intensity and the ranges of different water treatment methods and locations in California. Groundwater requires more energy (0.34 kWh per m^3) than surface water (0.15 kWh per m^3) because of the higher cost of pumping water. The data for the energy requirement of water delivery and treatment are from various studies covering different levels of completeness. Thus, the results are only used for reference. In the future, comparisons should be made with better information and a more comprehensive study of the energy requirement that includes all the phases of water delivery and the same level of treatment. The energy requirement of providing non-potable use of stormwater is based on one available study, while the energy requirements of other types of water are based on multiple analyses.

The delivery and treatment of brackish water, recycled water, and desalinated seawater for potable use require 0.94, 1.05, and 3.25 kWh per m^3 on average, respectively. For non-potable use, recycled water and stormwater require 0.89 kWh of electricity per m^3 because stormwater can be mixed with recycled water and treated in the same facility.

GHG emissions

The GHG emissions of the studied water sources are collected from a study analyzing California's life-cycle emissions of water production [49]. Table 4 shows average GHG emissions and their ranges. The extraction and treatment of 1 m^3 of groundwater and recycled water generate about 0.25 and 0.71 kg CO_2 eq., respectively. Desalinated brackish water and seawater are more CO_2 intensive than the previous two, 1.6 and 2.4 kg CO_2 eq. per m^3, respectively. GHG emissions from desalination are due to electricity consumption during facility operation, and the amount of emissions vary depending on the GHG intensity of the electricity mix. The carbon footprints of water supplies calculated from the previous studies in table 4 relied on regionalized average emission factors from the grid mix of the WECC electricity region, which provides electricity to California.

Stocks

The estimated stock of brackish groundwater is 3.9 trillion m^3 [46]. The stock of recycled water is estimated based on the amount of wastewater generated in California from the state-wide water recycling survey in 2015, and is put at 1.5 billion m^3 per year [51]. The estimated annual stock of stormwater in Southern California and the San Francisco Bay region ranges from 520 million to 780 million m^3 [45]. There are no reliable data on the stocks of groundwater.

The combined stormwater and recycled water supply potentials could either increase the share of alternative water use in urban land irrigation from 4.6% to 48% or increase the ratio of alternative water in agricultural land irrigation from 0.82% to 5.4%. If stormwater and recycled water were applied to irrigation in California, the agricultural cost would increase by $900 million (1.8% of California's annual agricultural revenue [54]) and the energy impact would increase by 710 GWh (0.28% of California's annual electricity consumption [55]). Therefore, these costs are not prohibitive.

Current production capacities

The current production capacity of each water source in California is based on current water treatment facilities and most of them meet potable use standards. The stormwater treatment capacity (133 million m^3) is estimated based on the total treatment quantity of the metropolitan area of Los Angeles and applying a similar amount of captured stormwater to the San Francisco Bay Area [46]. The annual production quantity of brackish water is 172 million m^3 according to a study on existing desalinated water facilities [56]. The recycled water production quantity is estimated from the production volumes of current recycled water facilities, and the total amount is 880 million m^3 per year [51]. The quantity of desalinated seawater (666 million m^3 per year) is estimated based on installed and proposed seawater desalination facilities in California [52]. Compared with the stocks of other alternative water sources, only a small portion of stormwater and recycled water, and an extremely small portion of brackish water and seawater have been captured or treated in California.

Based on table 4, we conclude that there is a large potential for expanding the treatment and use of alternative water sources for irrigation in California.

Water use in the food processing industry

We have estimated the current water consumption in food processing in California. We collected water use data for common food types such as almonds, carrots, pears, tomatoes, and cooking oil. We also estimated the consumption of each food type in California based on the US average consumption. Due to lack of precise data, we calculated the water consumption in food processing for the food consumed in California. Data and calculation used in the analysis can be found in the Supplementary Information section S8. Our estimate is that the water consumption in food processing in California was 44.6 million m^3 in 2017. If we assume the food produced in California is processed in California, 230 million m^3 of water will be needed for food processing per year. Substituting conventional water by alternative water is possible because the supply of alternative water (1.8 billion m^3) greatly exceeds the amount of water currently used in the food processing industry.

Case studies of high-value produce

California is one of the most productive agricultural areas and a major producer of many agricultural products in the United States. To explore the energy, GHG emissions, and cost implications of using alternative sources of water, this study selected four high-value fruits and vegetables: avocado, celery, lemon, and strawberry. They have different irrigation requirements and require different production inputs. In 2017, California's shares of US production of these four produce were 94% for avocado, 95% for celery, 79% for lemon, and 79% for strawberry [54].

A previous study by Bell *et al* analyzing these four fruits and vegetables focused on the environmental impacts of production using conventional irrigation water sources, recycled secondary or advanced water, and desalinated water in one hub of production, Ventura County [57]. In the current study, the locations of crop production are not limited to Ventura County, but are found across California and are considered representative of statewide production practices [58–61]. We used the latest available production data (packaging, biocides, fertilizers, direct electricity, direct fuels) and the most comprehensive data covering different irrigation scenarios that require different irrigation quantities of recycled water, desalinated brackish water and seawater, conventional water, and stormwater. A comparison between our study (table S1.1 is available online at stacks.iop.org/ERC/2/055003/mmedia) and the Bell *et al* paper (table S1.2) can be found in the Supplementary Information. Two other advances of our study include filling in the gaps on various packaging types and materials and performing an uncertainty evaluation of the credibility and representativeness of the data using the 'Pedigree matrix' approach [62]. Our study performed analysis for and comparison of one nutritional serving size of the four produce instead of uniformly one kilogram of each.

Figure 1 shows the calculated GHG emissions per serving when using alternative water sources. The emissions for one kilogram, and a cost estimate and energy consumption for one serving size and one kilogram of the four crops can be found in the Supplementary Information (figures S4–S6). According to the US Department of Agriculture, the serving sizes for strawberry and celery are 144 grams (1 cup) and 51 grams (½ cup), respectively [63]. Due to unavailability of published guidance, we used 1 lemon and ½ avocado as their respective serving sizes.

BAU (business-as-usual) represents the current production scenario which uses conventional water for irrigation. Figure 1 shows that the GHG emissions of strawberries are the highest, and that emissions from applied water contribute 17%, 12%, 4.1%, and 1.7% to the total emissions of avocados, lemons, celery, and strawberries, respectively. The use of materials (mostly from packaging) are the top contributor to emissions, 66%, 47%, 46%, and 26% for strawberries, celery, avocados, and lemons, respectively. Diesel use also contributes quite a large portion of the total emissions, 28%, 18%, and 14% for celery, lemons, and strawberries, respectively. (Data for diesel use for avocados are not available).

Switching from the current water supply to stormwater or recycled water would increase the total emissions by 3.0%, 7.8%, 11%, and 27% for strawberry, celery, lemon, and avocado, respectively. Changing to desalinated brackish water would increase the emissions by 23%, 58%, 150%, and 210% for strawberry, celery, lemon, and avocado, respectively. Using desalinated seawater would increase the emissions by 35%, 88%, 230%, and 320% for strawberry, celery, lemon, and avocado, respectively.

Uncertainty evaluation

The uncertainties associated with the data were evaluated through the data quality ('Pedigree') matrix method [62] that highlights the where uncertainty is likely to occur in the analysis and data. Several LCA studies and one the most widely used LCA databases, ecoinvent, use the Pedigree method for evaluating data quality [64–67].

We evaluated the data for cost, energy consumption, and GHG emissions of water supplies. We examined the major sources of uncertainty and scored 6 main data sources using the Pedigree matrix for each of them. Figures S9.1–S9.6 in the Supplementary Information show the selections of the Pedigree criteria for the mentioned data.

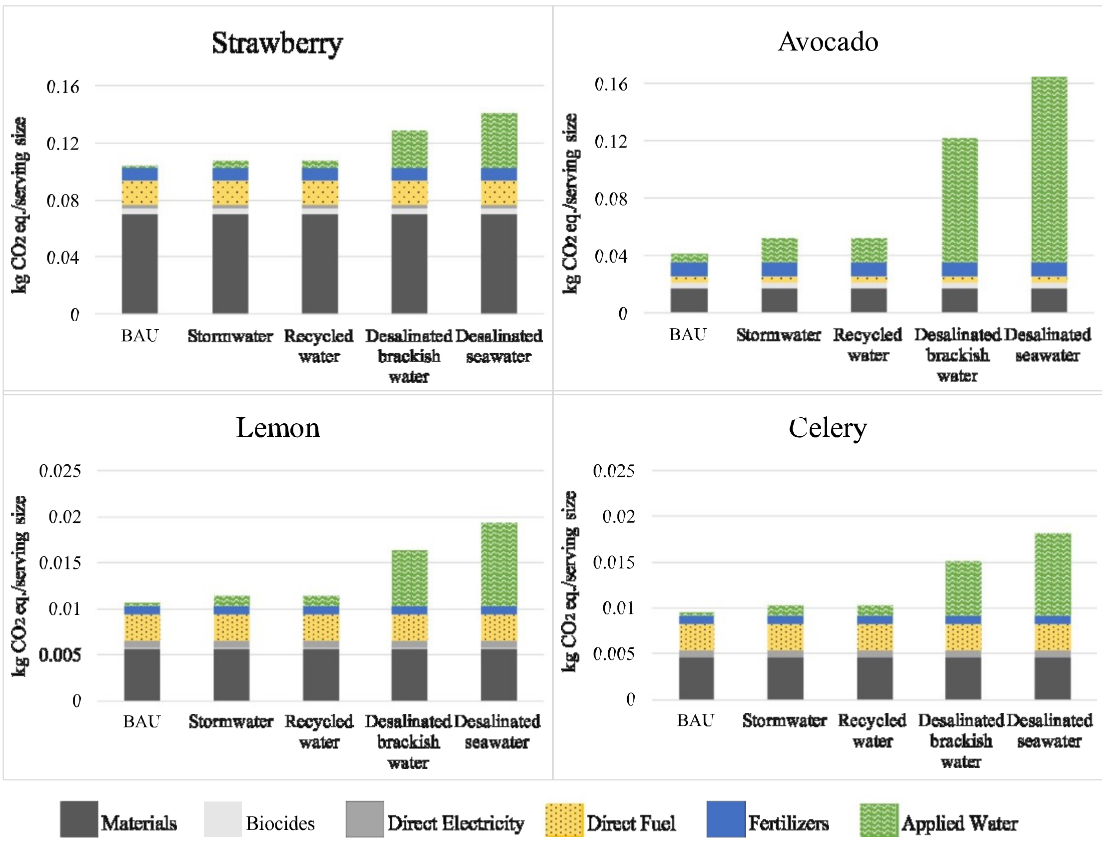

Figure 1. GHG emissions of avocado, celery, lemon, and strawberry production under different water supply scenarios in California for one serving size. The upper and lower two plots are on the same x-axis scale.

The trend from the scores in the Pedigree matrices showed that the uncertainty of energy consumption data for water supplies was found to be low. The estimated cost and GHG emissions of the water supplies had low and moderate uncertainties, respectively. The cost, energy consumption, and GHG emissions data for the four crops were labeled low uncertainty.

Overall, we found that the uncertainties in the data were low.

Discussion

We have analyzed the potential use of alternative water sources in irrigation in California by examining their associated costs, capacities, stocks, energy requirements, and GHG emissions. Recycled water and stormwater have higher potential than desalinated brackish water and seawater for irrigation from economic perspective, and they have been used in many places in California already.

Stormwater has the least cost among the alternative water supplies. For non-potable use, the cost of stormwater supply is lower than the cost of groundwater supply. The potential supply of stormwater in California ranges from 520 million to 780 million m^3 per year, depending on the actual quantity of stormwater in that year [41]. However, the uncertainties associated with meteorological and climatic conditions should be considered in the planning of stormwater supply. The benefits of using recycled water include reducing water withdrawals and corresponding ecological effects, increasing water supply, and reducing energy requirements and costs at least in some parts of California. If the potential for annual wastewater reuse is equivalent to the amount of municipal wastewater, the estimated recycled water potential in California is 1.5 billion m^3 [51]. However, the amount of available recycled water in the future could decline because of improvements in water use efficiency.

Water cost highly depends on the scale of the treatment facility. The cost of stormwater for potable use can be 2.5 times greater from a small-scale facility (treating less than 1.85 million m^3) when compared to a large-scale facility. Since water treatment for non-potable use is much cheaper than for potable use, increasing the non-potable use of alternative water such as toilet flushing and car washing is another way to reduce the cost of water supply. For example, using non-potable brackish water for highway landscaping irrigation is an economical solution of reducing the demand for conventional water.

Alternative water requires higher energy consumption and generates more GHG emissions than conventional water does. For example, switching from the current to an alternative water supply for growing strawberries would increase the emissions by 3.0%–35%. As the electricity grid becomes greener by employing more renewable energy, the overall GHG emissions from the water supply could be reduced. On-site energy generation from bio-digested sludge at individual wastewater treatment plants could lower grid electricity usage and GHG emissions of recycled water.

Compared with the study by Bell et al [57] our study has found that the life-cycle cycle GHG emissions of avocado, celery, lemon, and strawberry using conventional water were increased by 70%, 86%, 39%, and 16%, respectively, largely due to the inclusion of the packaging materials of cartons and trays which are quite emissions-intensive to manufacture.

Since the water demand in California has exceeded supply in many years, and the gap between demand and supply is likely to widen due to climate change (if not also due to population growth), there is an essential need for promoting the use of alternative water sources and developing the corresponding treatment facilities [68]. Though the switch to alternative water will increase costs, energy demand, and GHG emissions, the use of alternative materials in agricultural production and sales (especially packaging) needs to be explored as potentially offsetting the higher economic, energy, and emissions costs of alternative water supplies.

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